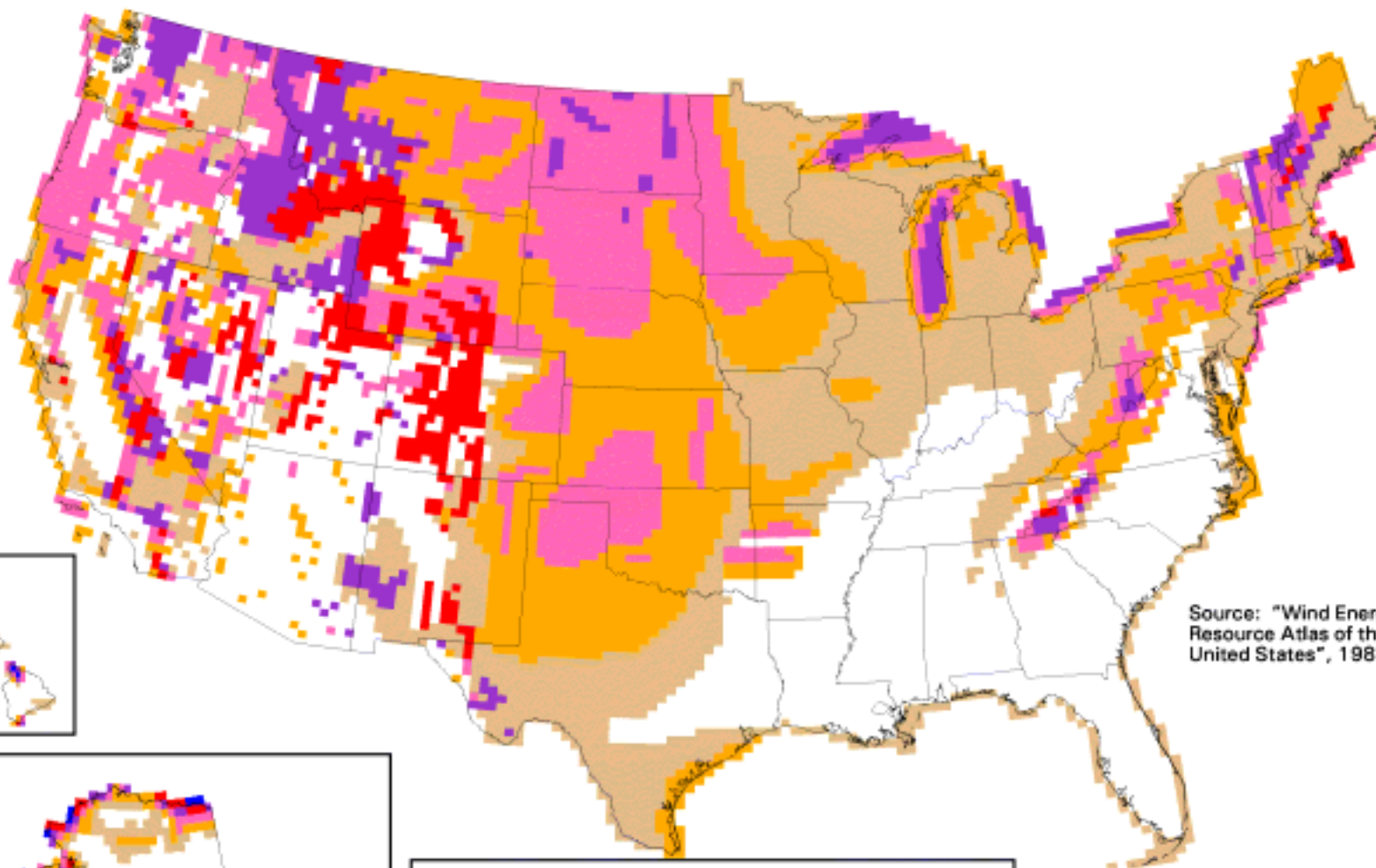# Wind Resource Assessment and Mapping

D. Elliott, M. Schwartz, and G. Scott

National Renewable Energy Laboratory

Golden, Colorado
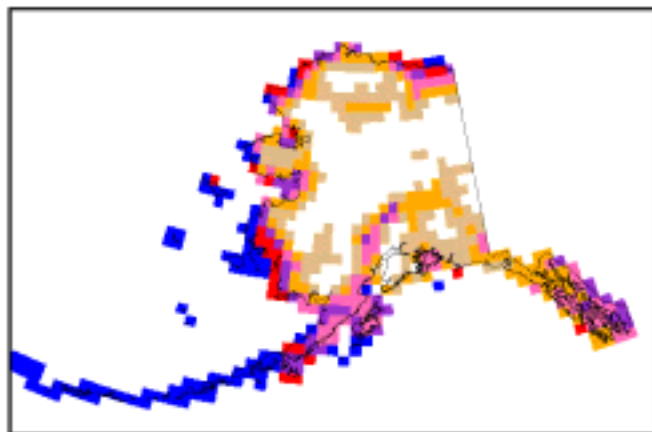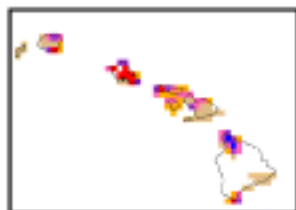
Wind Workshop for State Lands

April 29, 2003

NREL Golden, Colorado

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United States - Wind Resource Map

Source: "Wind Energy Resource Atlas of the United States", 1987

Wind Power Classification

Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m²	Wind Speed[a] at 50 m m/s	Wind Speed[a] at 50 m mph
2	Marginal	200 - 300	5.6 - 6.4	12.5 - 14.3
3	Fair	300 - 400	6.4 - 7.0	14.3 - 15.7
4	Good	400 - 500	7.0 - 7.5	15.7 - 16.8
5	Excellent	500 - 600	7.5 - 8.0	16.8 - 17.9
6	Outstanding	600 - 800	8.0 - 8.8	17.9 - 19.7
7	Superb	800 - 1600	8.8 - 11.1	19.7 - 24.8

[a] Wind speeds are based on a Weibull k value of 2.0

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National Renewable Energy Laboratory

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20-MAR-2000 1.1.5

Wind Power Classification

Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m^2	Wind Speed[a] at 50 m m/s	Wind Speed[a] at 50 m mph
2	Marginal	200 - 300	5.6 - 6.4	12.5 - 14.3
3	Fair	300 - 400	6.4 - 7.0	14.3 - 15.7
4	Good	400 - 500	7.0 - 7.5	15.7 - 16.8
5	Excellent	500 - 600	7.5 - 8.0	16.8 - 17.9
6	Outstanding	600 - 800	8.0 - 8.8	17.9 - 19.7
7	Superb	800 - 1600	8.8 - 11.1	19.7 - 24.8

[a] Wind speeds are based on a Weibull k value of 2.0

Comparison of Digital Wind Map from 1987 U.S. Wind Atlas and New (2000) High-Resolution (1-km²) Wind Map North and South Dakota

1987

2000

Wind Power Classification

	Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m²	Wind Speed[a] at 50 m m/s	Wind Speed[a] at 50 m mph
	2	Marginal	200 - 300	5.6 - 6.4	12.5 - 14.3
	3	Fair	300 - 400	6.4 - 7.0	14.3 - 15.7
	4	Good	400 - 500	7.0 - 7.5	15.7 - 16.8
	5	Excellent	500 - 600	7.5 - 8.0	16.8 - 17.9
	6	Outstanding	600 - 800	8.0 - 8.8	17.9 - 19.7
	7	Superb	800 - 1600	8.8 - 11.1	19.7 - 24.8

[a] Wind speeds are based on a Weibull k value of 2.0
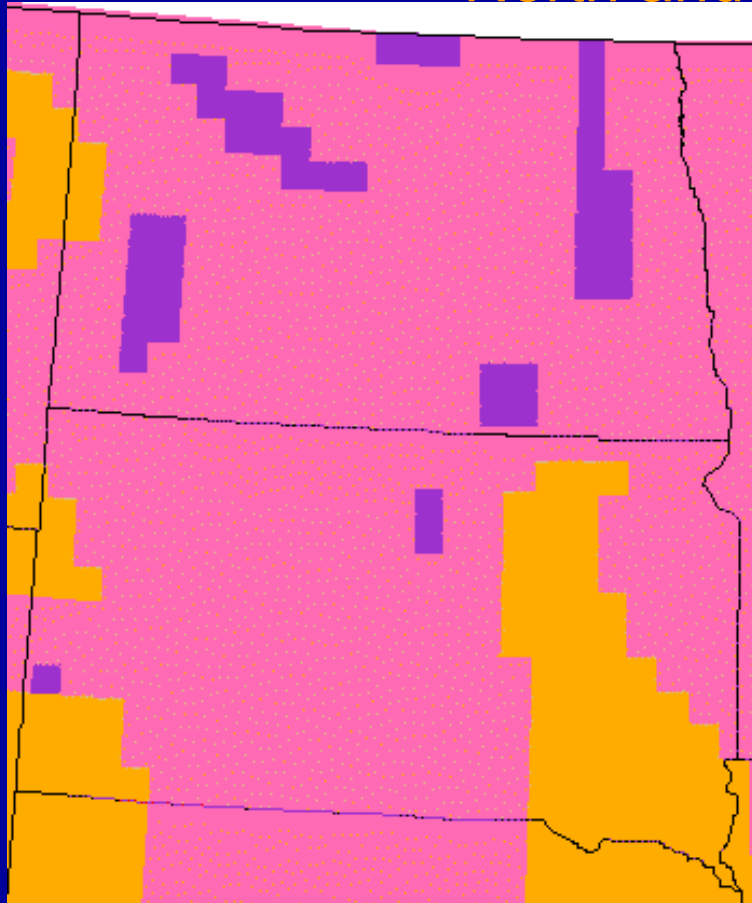
North Dakota - Wind Resource Map

Wind Power Classification

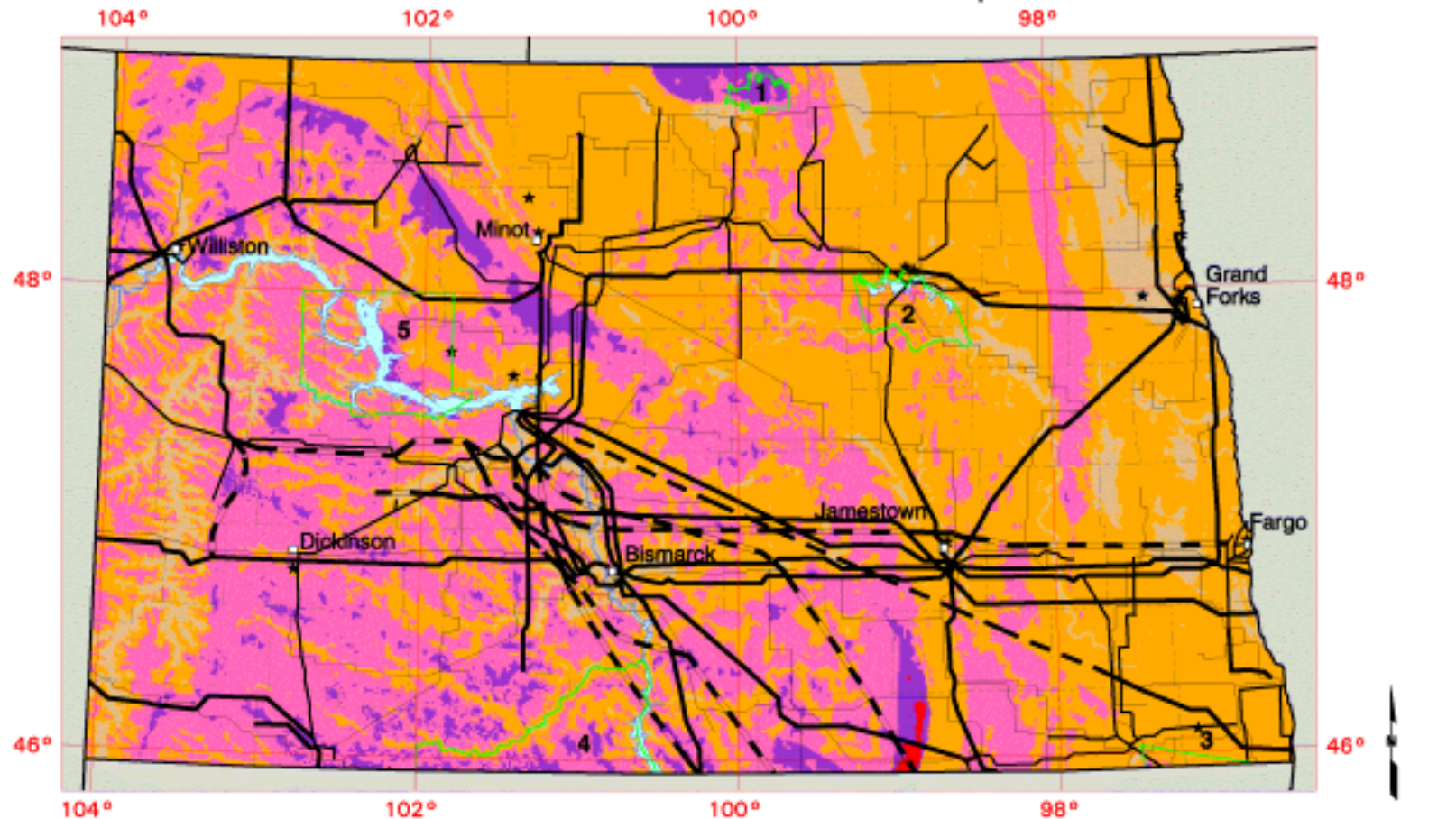| Wind Power Class		Resource Potential	Wind Power Density at 50 m W/m²	Wind Speed[a] at 50 m m/s	Wind Speed[a] at 50 m mph
	2	Marginal	200 - 300	5.6 - 6.4	12.5 - 14.3
	3	Fair	300 - 400	6.4 - 7.0	14.3 - 15.7
	4	Good	400 - 500	7.0 - 7.5	15.7 - 16.8
	5	Excellent	500 - 600	7.5 - 8.0	16.8 - 17.9
	6	Outstanding	600 - 800	8.0 - 8.8	17.9 - 19.7

[a] Wind speeds are based on a Weibull k value of 2.0

★ Meteorological Station with Wind Data
□ City or Town

Transmission Line Voltage

- 69 Kilovolts
- 115 Kilovolts
- 230 Kilovolts
- 345 Kilovolts
- Under Construction

Indian Reservations

1. Turtle Mountain
2. Devil's Lake Sioux
3. Lake Traverse
4. Standing Rock
5. Fort Berthold

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Why Re-Map the U.S. Wind Resource?

- Increased interest in wind energy development
  - U.S. Department of Energy's Windpowering America program
  - New state policies and funds available for renewable energy
  - Larger market for utility-scale and small wind turbines
    - Farm use and distributed generation
    - Need more detail than provided in 1987 Atlas
- Advanced mapping tools available
  - Better meteorological and topographic data sets
  - Increased utility of computer hardware and software

WIND POWER RELATIONSHIPS

$$P = \tfrac{1}{2} \, \rho \, A \, V^3$$

AVAILABLE POWER   AIR DENSITY   SWEPT AREA   WIND VELOCITY CUBED

EXAMPLE: SAME TURBINE, SEA LEVEL, DIFFERENT SITE

$$P = KV^3$$

WIND VELOCITY = v $P_1 = Kv^3$

WIND VELOCITY = $2v$ $P_2 = 8Kv^3$

$$P_2 = 8P_1$$

EXAMPLE: DIFFERENT TURBINE, SEA LEVEL, SAME SITE

$$P = CD^2$$

ROTOR DIAMETER = d $P_1 = Cd^2$

ROTOR DIAMETER = $2d$ $P_2 = 4Cd^2$

$$P_2 = 4P_1$$

Comparison of Annual Average Wind Power at Four Sites with Identical Annual Average Wind Speeds at 10 m

| Site	Annual Average Wind Speed, m/s (mph)	Annual Average Wind Power Density, W/m²	Wind Power Power Class
Constant Wind Speed (hypothetical)	6.3 (14)	150	2-3
Culebra, Puerto Rico	6.3 (14)	220	4
Tiana Beach, New York	6.3 (14)	285	5
San Gorgonio, California	6.3 (14)	365	6

S9106046.5

WIND VELOCITY VERSUS ALTITUDE

$$\frac{V}{V_o} = \left(\frac{H}{H_o}\right)^n$$

WHERE: V_o = REFERENCE WIND VELOCITY

H_o = REFERENCE HEIGHT

n = DEPENDENT EXPONENT
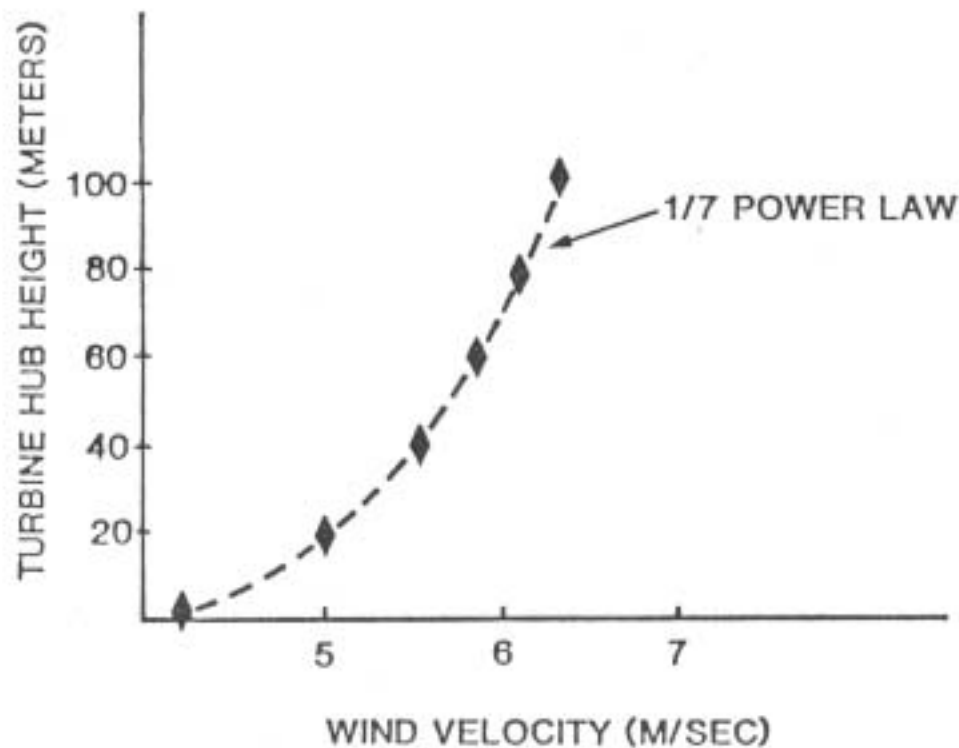
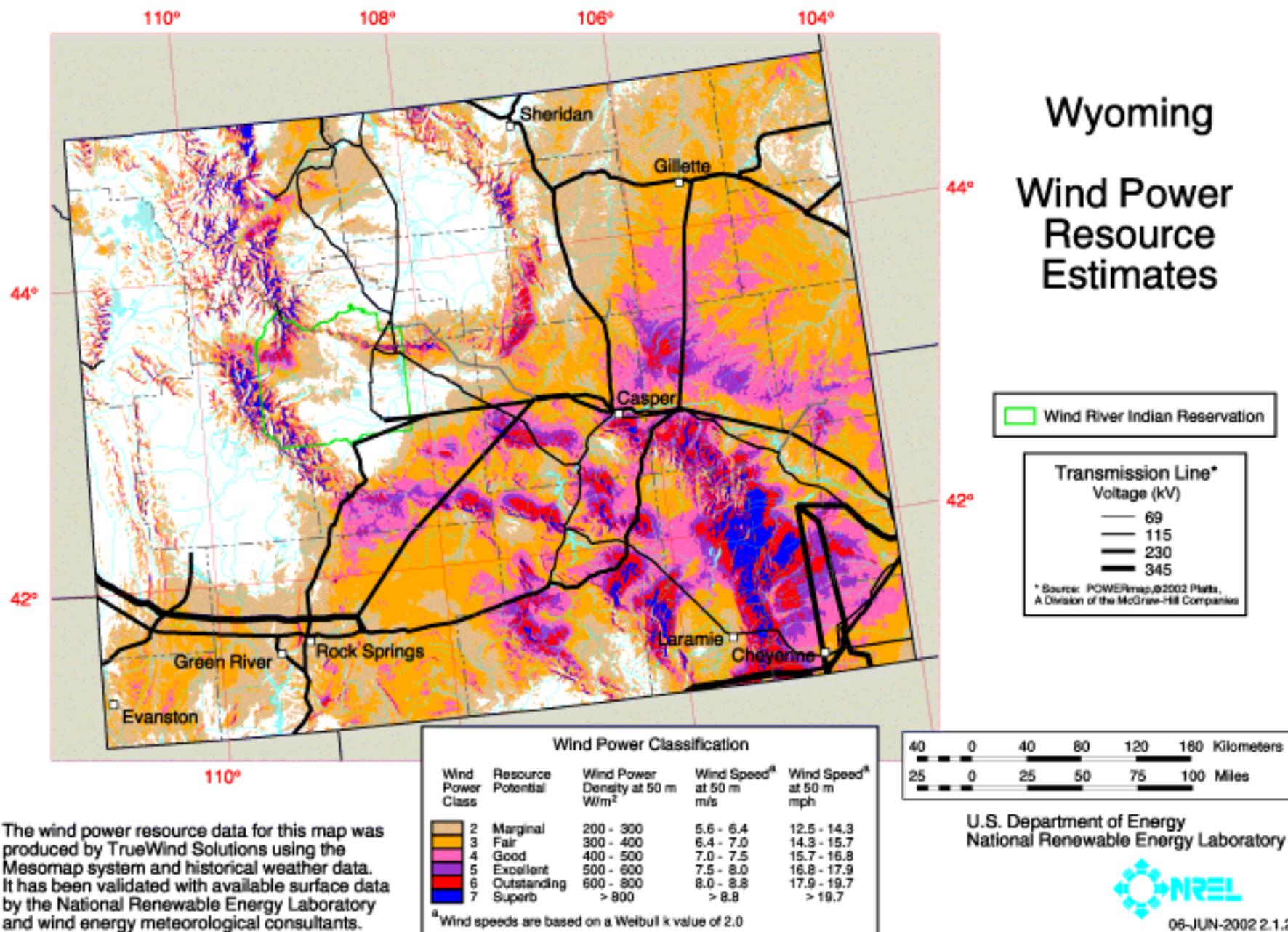# Wind Mapping Approach

- Computerized mapping approach using Geographical Information System (GIS) software (ArcInfo® and ArcView®)
- Designed for regional wind mapping (not micrositing)
- Combination of analytical, numerical, and empirical methods
- Does not depend on high-quality surface wind observations (but it helps)
- Produces high resolution (1 km^2 or finer) wind power maps

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Data Collection for Assessment

- Meteorological data sets
    - surface station data (weather observations)
    - upper-air data (weather balloon obs)
    - model output data (Reanalysis, etc)
- Other wind measurement data available from region
- Digital terrain (1 km^2 or finer) and geographic data

NREL

Wyoming

Wind Power Resource Estimates

| 44° |
| 42° |

Map labels: Sheridan, Gillette, Casper, Green River, Rock Springs, Evanston, Laramie, Cheyenne

Coordinate labels: 110°, 108°, 106°, 104°, 44°, 42°

☐ Wind River Indian Reservation

Transmission Line*
Voltage (kV)

———	69
———	115
———	230
▬▬▬	345

* Source: POWERmap,©2002 Platts,
A Division of the McGraw-Hill Companies

Wind Power Classification

Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m²	Wind Speed[a] at 50 m m/s	Wind Speed[a] at 50 m mph
2	Marginal	200 - 300	5.6 - 6.4	12.5 - 14.3
3	Fair	300 - 400	6.4 - 7.0	14.3 - 15.7
4	Good	400 - 500	7.0 - 7.5	15.7 - 16.8
5	Excellent	500 - 600	7.5 - 8.0	16.8 - 17.9
6	Outstanding	600 - 800	8.0 - 8.8	17.9 - 19.7
7	Superb	> 800	> 8.8	> 19.7

[a] Wind speeds are based on a Weibull k value of 2.0

Scale:

| 40 | 0 | 40 | 80 | 120 | 160 | Kilometers |
| 25 | 0 | 25 | 50 | 75 | 100 | Miles |

The wind power resource data for this map was produced by TrueWind Solutions using the Mesomap system and historical weather data. It has been validated with available surface data by the National Renewable Energy Laboratory and wind energy meteorological consultants.

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06-JUN-2002 2.1.2

Washington - Wind Power Resource Estimates

Indian Reservation

1	Makah
2	Ozette
3	Quileute
4	Hoh
5	Quinault
6	Shoalwater Bay
7	Lower Elwha
8	Jamestown
9	Skokomish
10	Squaxin Island
11	Chehalis
12	Nisqually
13	Puyallup
14	Muckleshoot
15	Port Madison
16	Port Gamble
17	Tulalip
18	Swinomish
19	Lummi
20	Nooksack
21	Upper Skagit
22	Stillaquamish
23	Sauk-Suiatlle
24	Colville
25	Spokane
26	Kalispel
27	Yakama

Transmission Line*
Voltage (kV)

- 69
- 115
- 230 - 287
- 345
- 500
- 1000 (DC)

* Source: POWERmap, © 2002
Platts, a Division of the McGraw-
Hill Companies

Wind Power Classification

Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m²	Wind Speed[a] at 50 m m/s	Wind Speed[a] at 50 m mph
2	Marginal	200 - 300	5.6 - 6.4	12.5 - 14.3
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[a] Wind speeds are based on a Weibul k value of 2.0

The wind power resource data for this map was produced by TrueWind Solutions using the Mesomap system and historical weather data. It has been validated with available surface data by the National Renewable Energy Laboratory and wind energy meteorological consultants.

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07-JUN-2002 1.1.11

Validation of Wind Maps

- Collaborative process among TrueWind, NREL, and consulting experts
- Validators -- NREL and expert consultants
  - use own methods and data
  - provide both quantitative scores and qualitative comments
  - provide validation results to NREL/TrueWind
- TrueWind
  - produces preliminary map for validators
  - reviews validation results to improve map
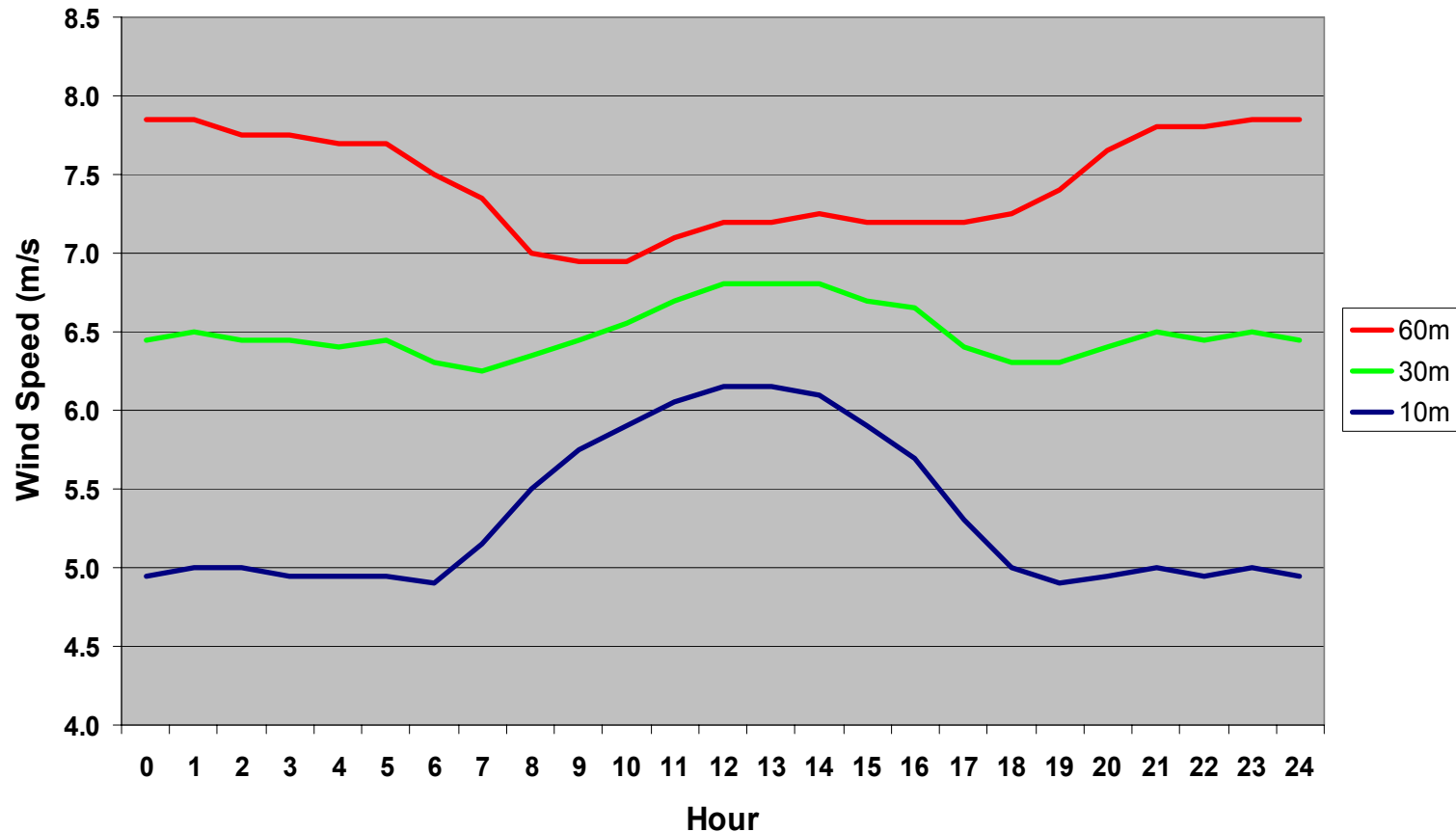 - produces final validated map

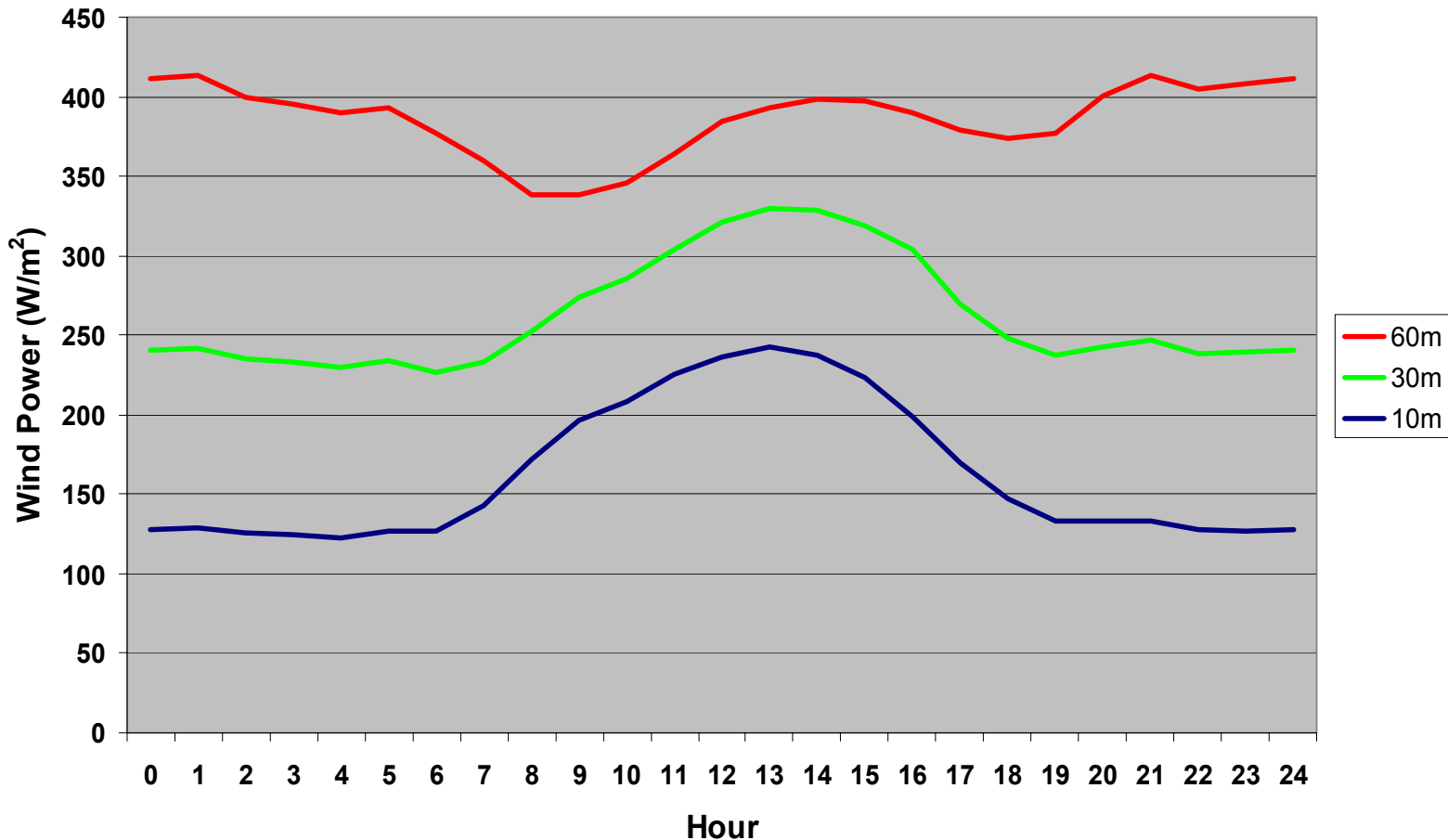Montana Annual Wind Speed Pattern by Region
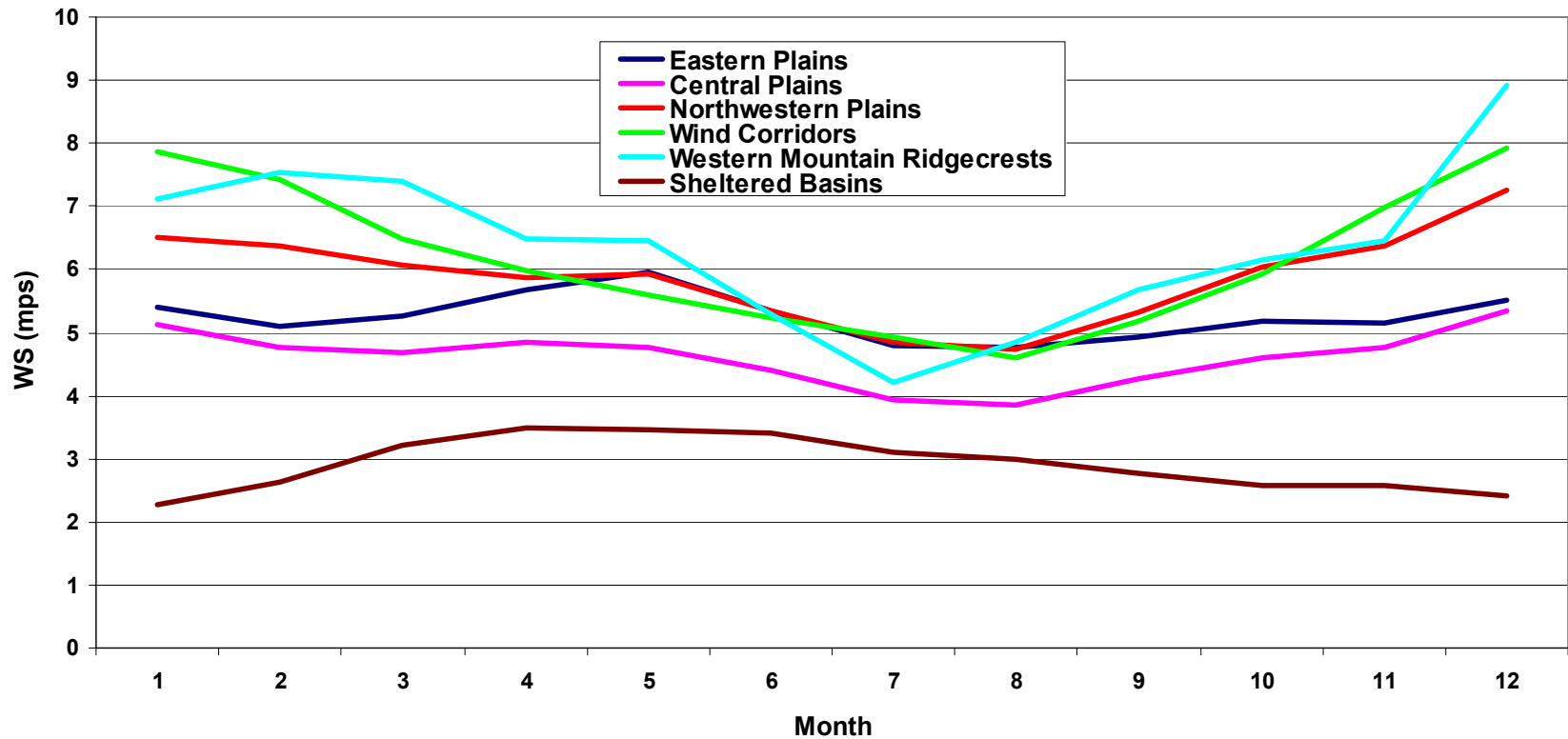
Diurnal Pattern at Livingston, MT
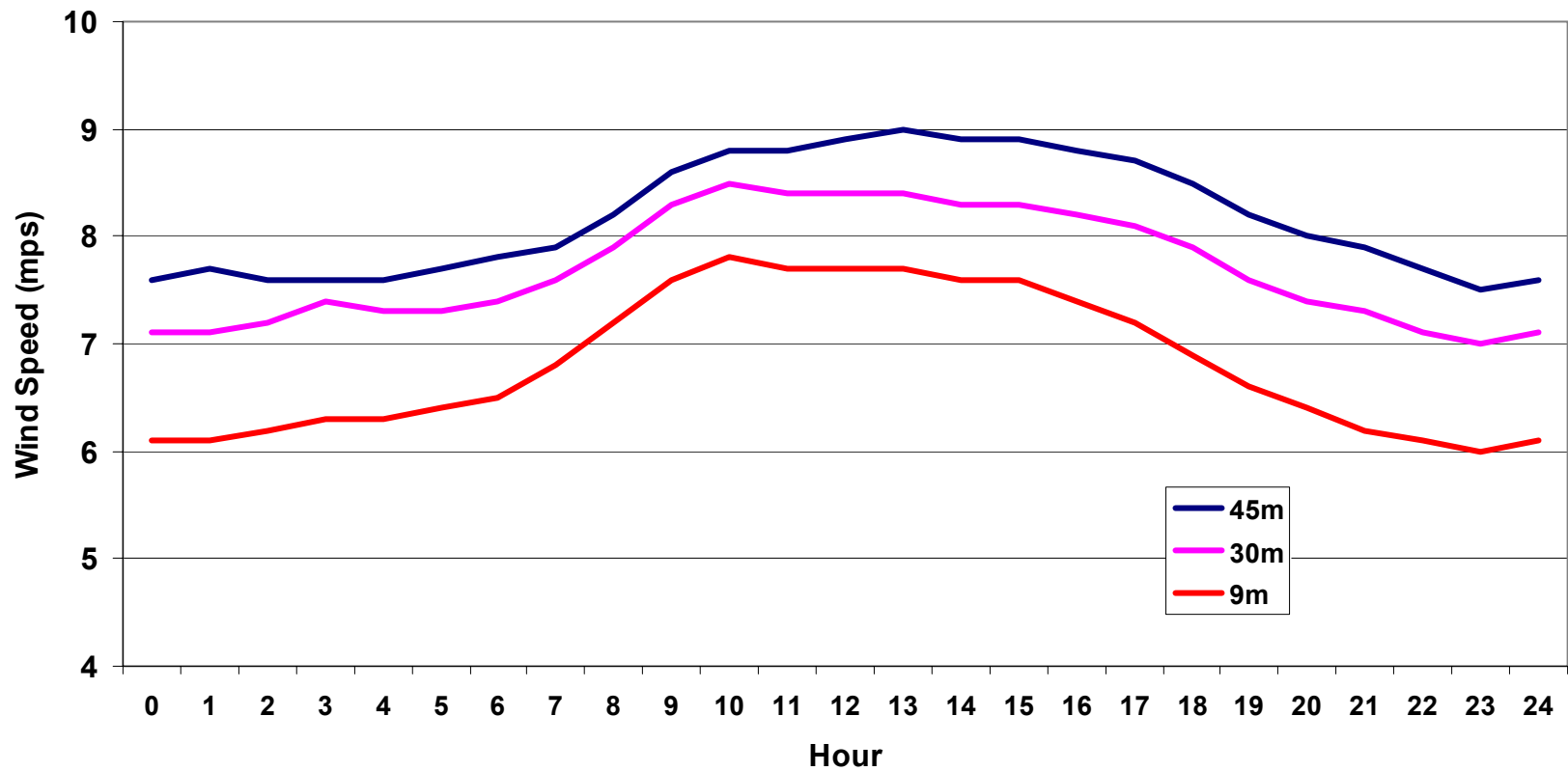
Wind Speed by Hour
Central Illinois Tall Towers

- Wind speed increases dramatically with height above ground
- Diurnal profile of wind changes with height above ground

Wind Power by Hour
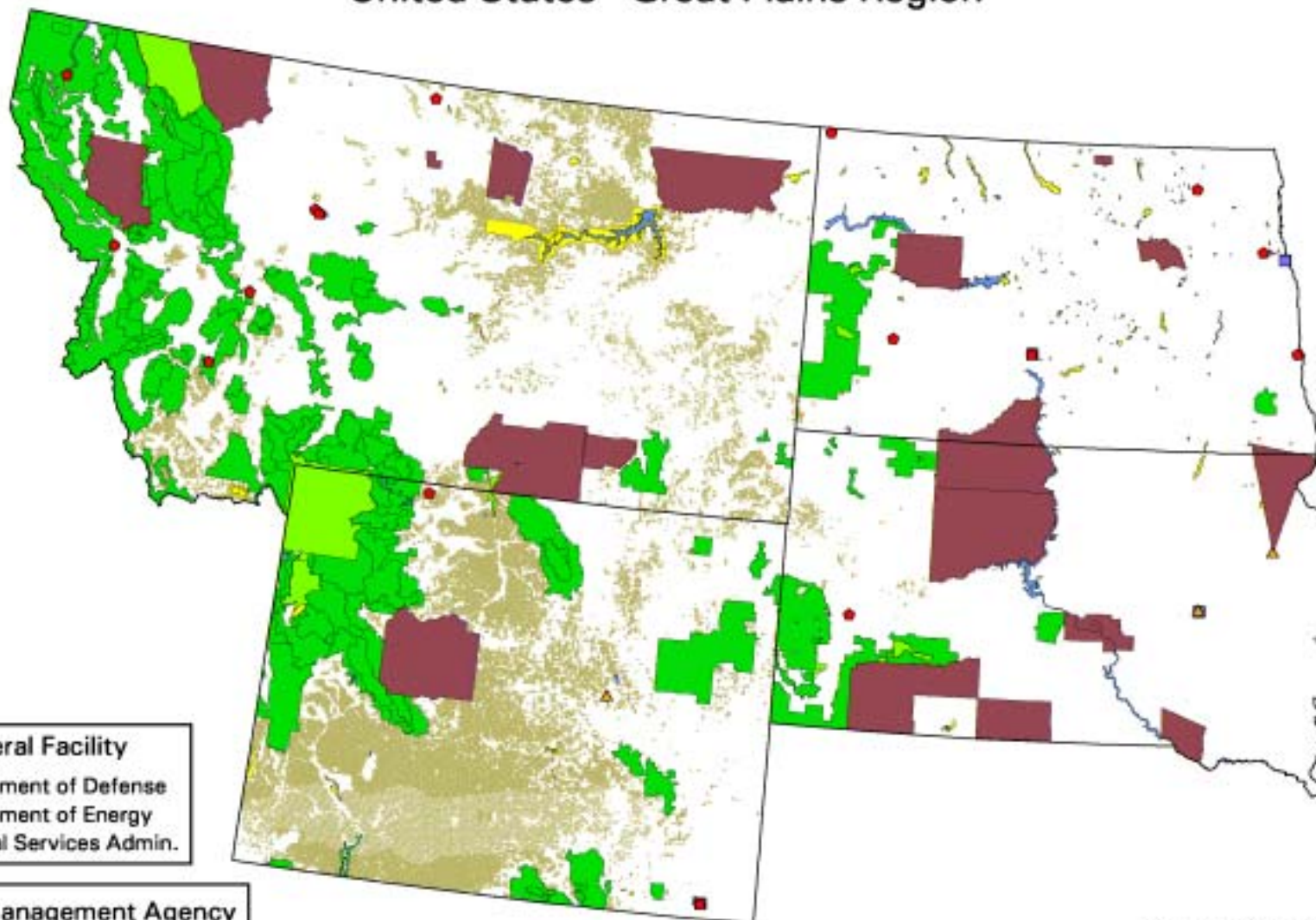**Central Illinois Tall Towers**

- Wind power increases at a greater rate than wind speed with height above ground

Integration of GIS Data Sets

- Topography (1-km^2)
  - Slope
  - Relative elevation
  - Aspect
- Transmission lines
- Meteorological Stations
- Federal lands and facilities
- Native American lands
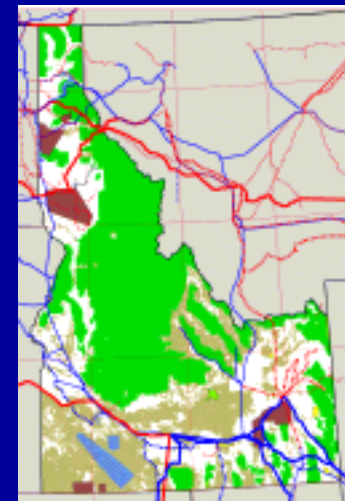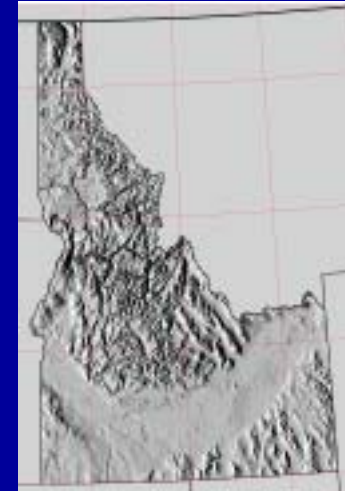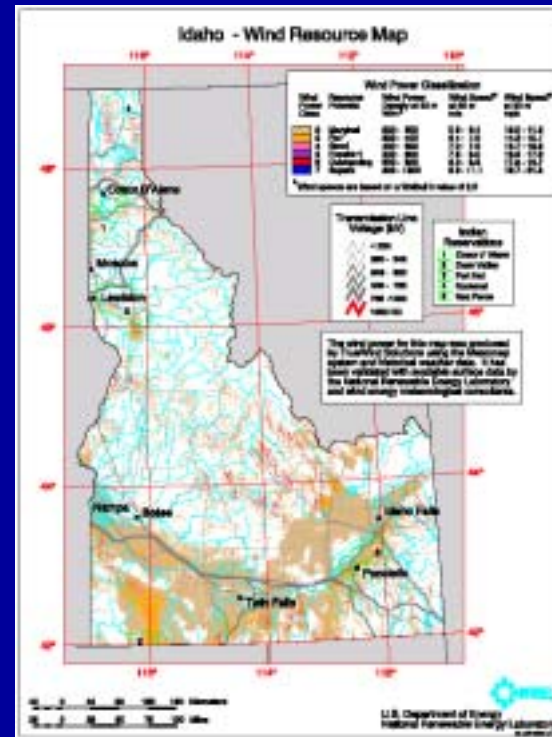
United States - Great Plains Region

Federal Facility
- ● Department of Defense
- ▲ Department of Energy
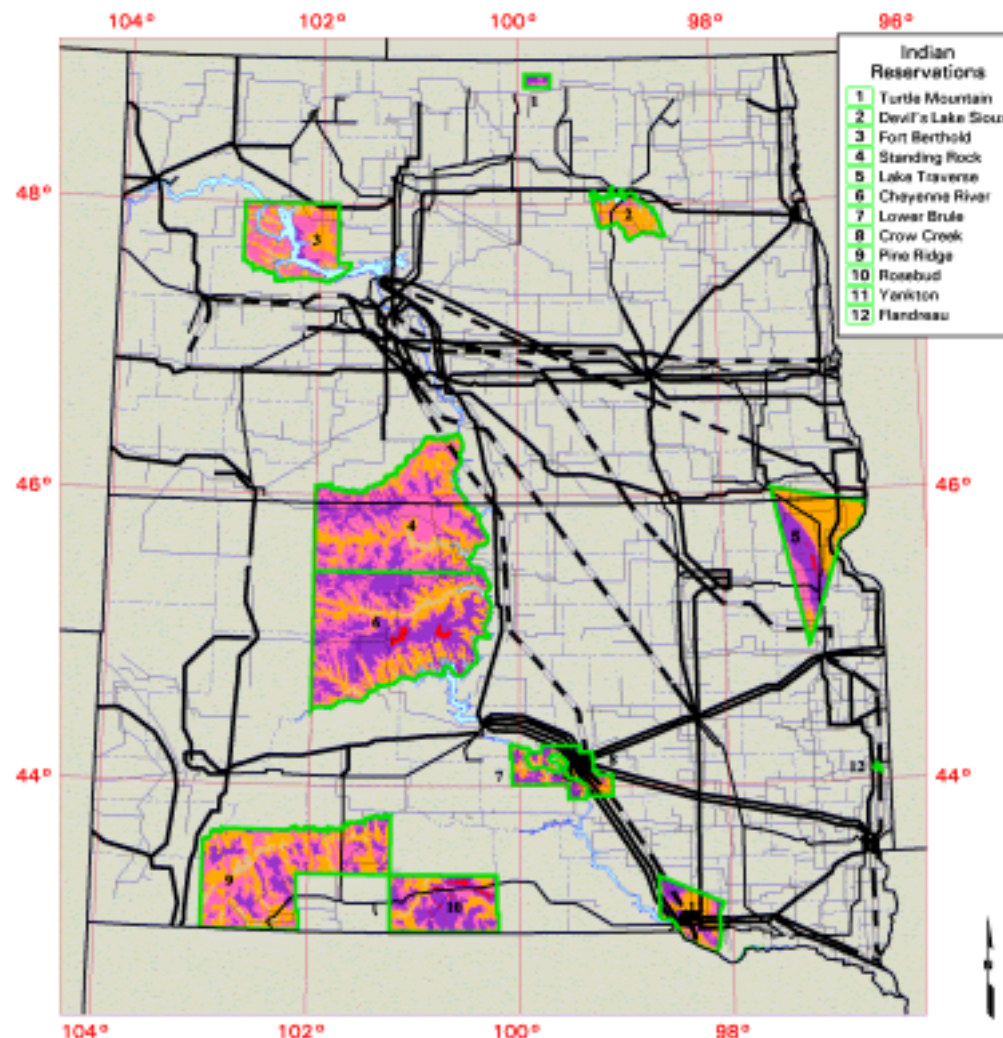- ■ General Services Admin.

Land Management Agency
- Indian Reservation or Alaska Native Village Area
- Department of Defense
- Forest Service
- National Park Service
- Bureau of Land Management
- Fish and Wildlife Service

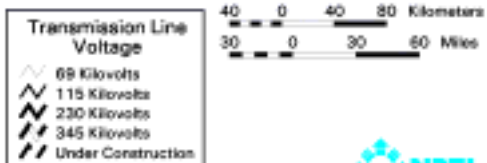US Dept. of Energy - National Renewable Energy Laboratory

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DM Heimiller 16-MAR-2000 2.1.1
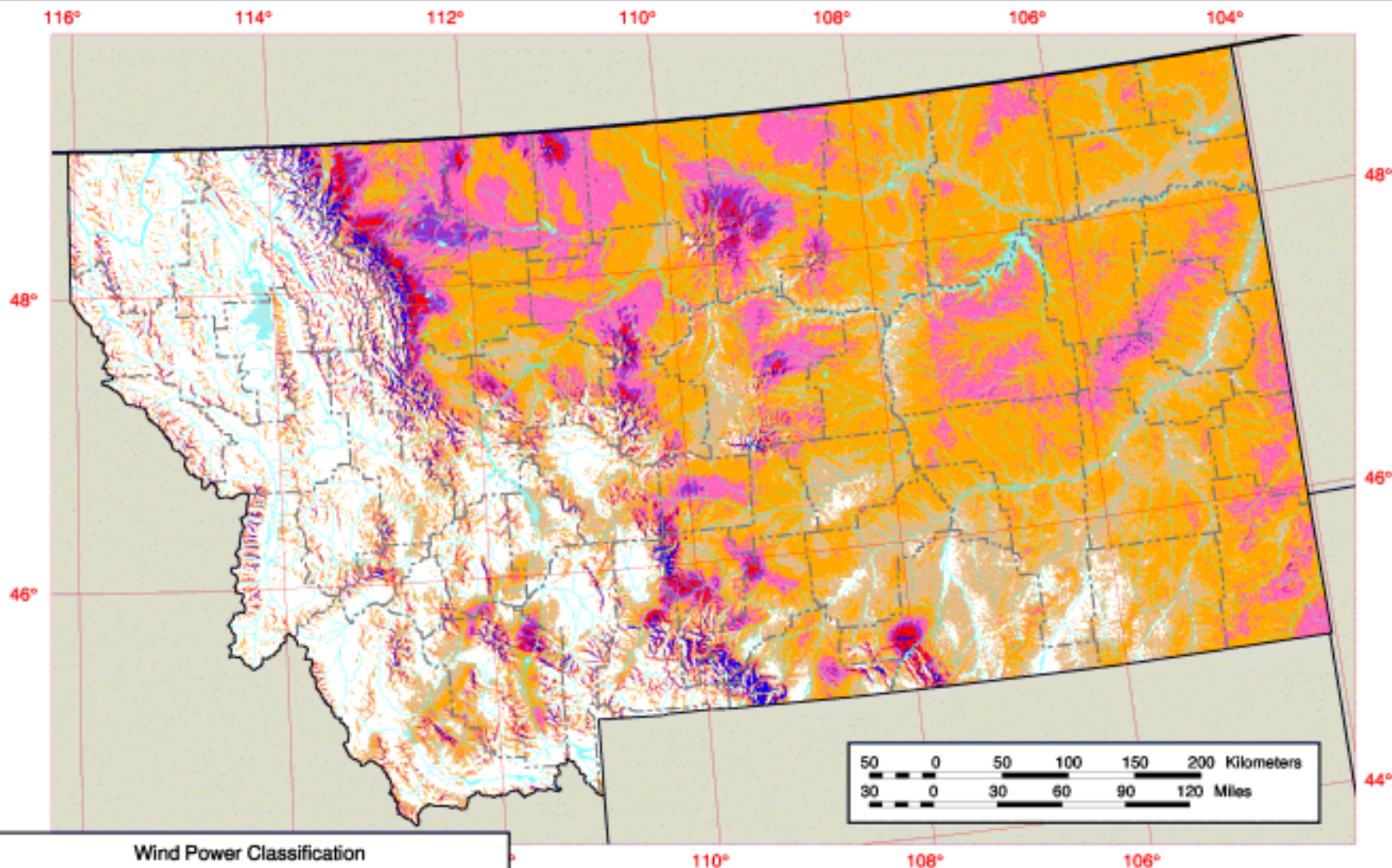
North and South Dakota - Wind Resource Map

Wind Power Classification

Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m^2	Wind Speed* at 50 m m/s	Wind Speed* at 50 m mph
2	Marginal	200 - 300	5.6 - 6.4	12.5 - 14.3
3	Fair	300 - 400	6.4 - 7.0	14.3 - 15.7
4	Good	400 - 500	7.0 - 7.5	15.7 - 16.8
5	Excellent	500 - 600	7.5 - 8.0	16.8 - 17.9
6	Outstanding	600 - 800	8.0 - 8.8	17.9 - 19.7
7	Superb	800 - 1600	8.8 - 11.1	19.7 - 24.8

*Wind speeds are based on a Weibull k value of 2.0

Transmission Line Voltage

- 69 Kilovolts
- 115 Kilovolts
- 230 Kilovolts
- 345 Kilovolts
- Under Construction

40 0 40 80 Kilometers
30 0 30 60 Miles

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Montana
Wind Power Resource Estimates

U.S. Department of Energy
National Renewable Energy Laboratory
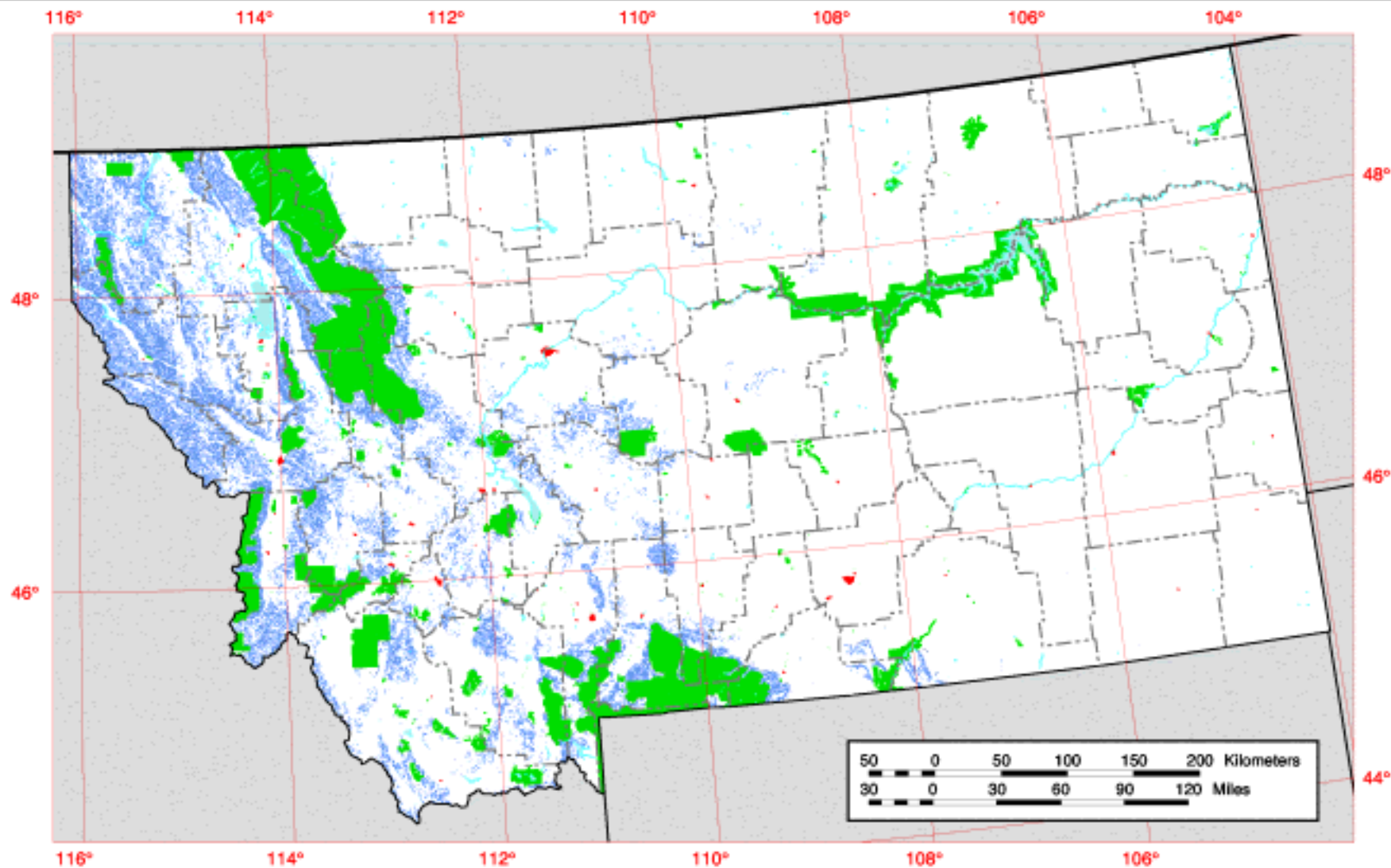
The wind power resource estimates were produced by TrueWind Solutions using their Mesomap system and historical weather data. This map has been validated with available surface data by the National Renewable Energy Laboratory and wind energy meteorological consultants.

12-MAR-2002 1.1.2

Wind Power Classification

Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m²	Wind Speed[a] at 50 m m/s	Wind Speed[a] at 50 m mph
2	Marginal	200 - 300	5.6 - 6.4	12.5 - 14.3
3	Fair	300 - 400	6.4 - 7.0	14.3 - 15.7
4	Good	400 - 500	7.0 - 7.5	15.7 - 16.8
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6	Outstanding	600 - 800	8.0 - 8.8	17.9 - 19.7
7	Superb	> 800	> 8.8	> 19.7

[a] Wind speeds are approximate and based on a Weibull k value of 2.0

Montana
Exclusions Used in
Windy Lands Analysis

U.S. Department of Energy
National Renewable Energy Laboratory

Excluded Areas*

- Water Bodies (i.e. lakes, reservoirs, wide rivers)
- Environmentally Sensitive State and Federal Lands (i.e. wildlife refuges, parks, wilderness areas)
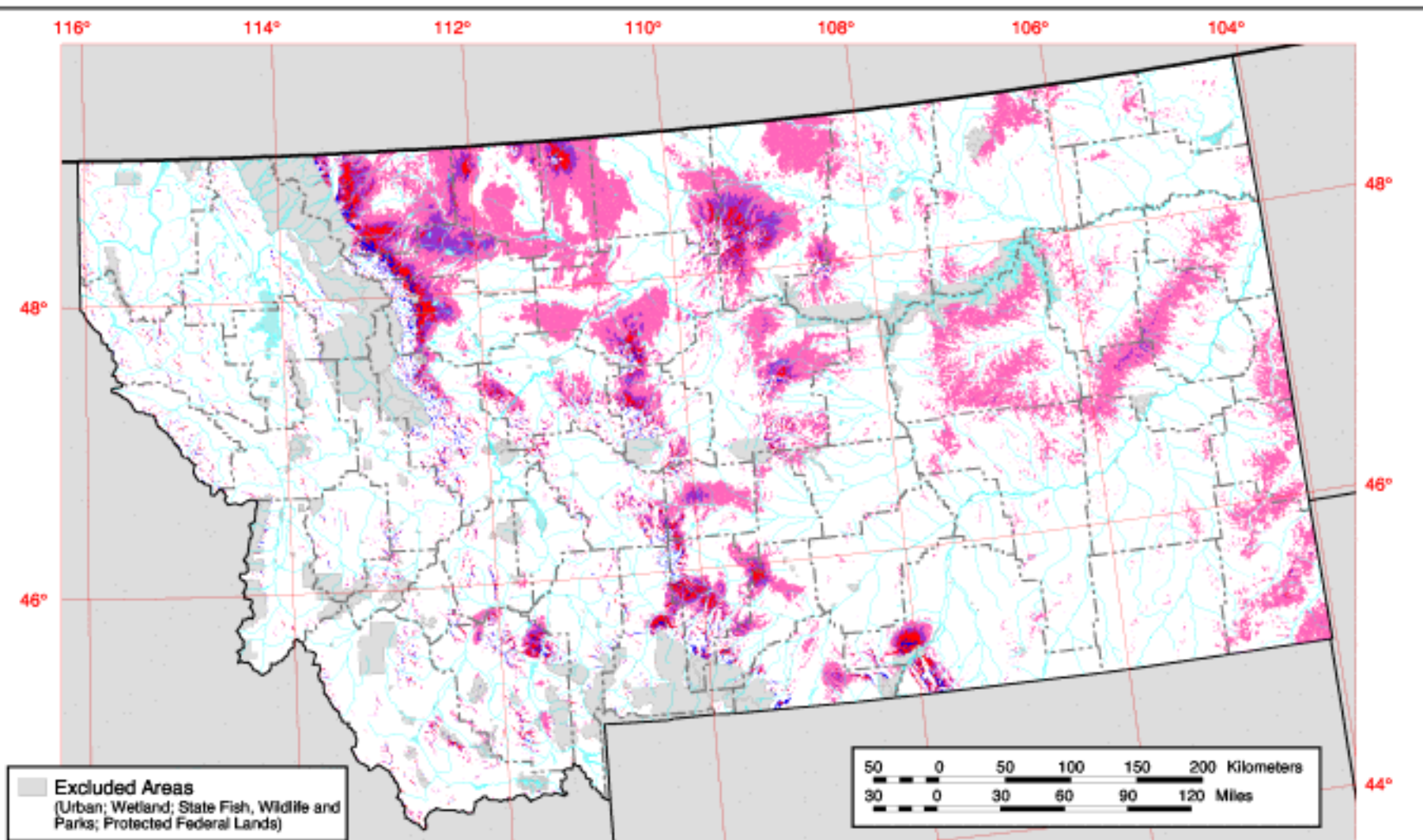- Major Urban Areas
- Slope > 20%

* Data shows no wetlands for Montana

NREL

11-APR-2002 1.1.8

Montana
Wind Power Resource Estimates

U.S. Department of Energy
National Renewable Energy Laboratory

The wind power resource estimates were produced by TrueWind Solutions using their Mesomap system and historical weather data. This map has been validated with available surface data by the National Renewable Energy Laboratory and wind energy meteorological consultants.

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11-APR-2002 1.1.6

Excluded Areas
(Urban; Wetland; State Fish, Wildlife and Parks; Protected Federal Lands)

| 50 | 0 | 50 | 100 | 150 | 200 | Kilometers |
| 30 | 0 | 30 | 60 | 90 | 120 | Miles |

Wind Power Classification

Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m²	Wind Speed[a] at 50 m m/s	Wind Speed[a] at 50 m mph
4	Good	400 - 500	7.0 - 7.5	15.7 - 16.8
5	Excellent	500 - 600	7.5 - 8.0	16.8 - 17.9
6	Outstanding	600 - 800	8.0 - 8.8	17.9 - 19.7
7	Superb	> 800	> 8.8	> 19.7

[a] Wind speeds are approximate and based on a Weibull k value of 2.0

Montana's Windy Land Area and Wind Potential

- Wind resource – class 4 and above (good-to-excellent wind for utility scale applications)
- Excluded areas:
  - Environmentally sensitive lands (parks, wilderness, etc)
  - Urban areas   – Steep slopes > 20%   – Water bodies
- Montana's windy land area
  - 67,210 square kilometers or 16,607,980 acres
  - 18% of state's total area (376,564 square kilometers)
  - Total windy land is slightly larger than state of West Virginia
- Montana's wind potential
  - 336,050 MW of potential installed nameplate capacity
  - Assumes 5 MW per square kilometer or 1 MW per 50 acres of windy land

NREL

Montana - State Lands
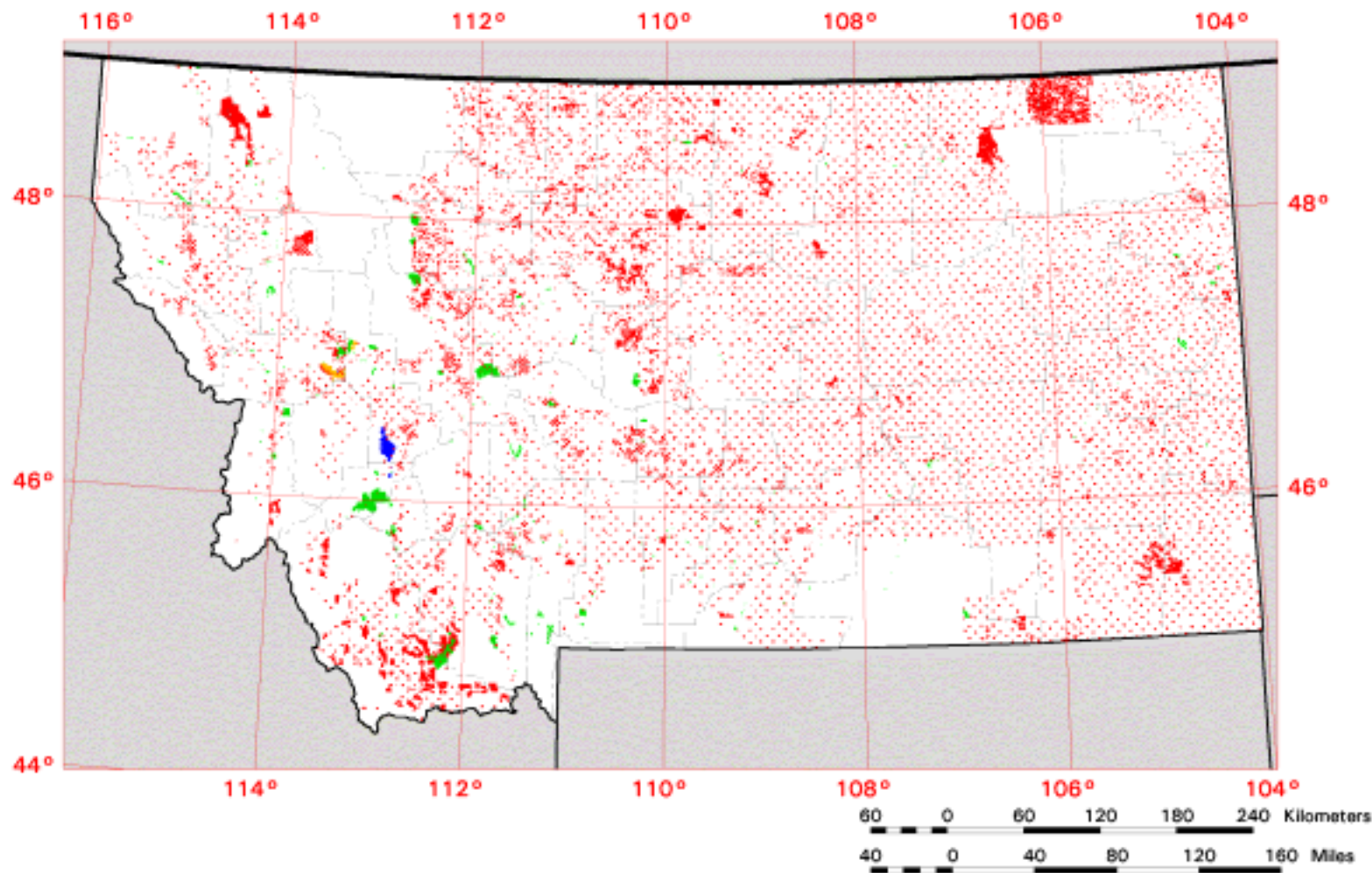
State Lands*
Owner

- 🟥 Montana State Trust Lands
- 🟩 Montana Fish, Wildlife, and Parks
- 🟧 Montana University System
- 🟦 Montana Institutions (prisons, hospitals)
- 🟪 Montana Department of Transportation

*Source: Montana Natural Heritage Program

U.S. Department of Energy
National Renewable Energy Laboratory

DM Heimiller 14-JUN-2001 2.1.3

Montana State Lands - Top 20 Potential Wind Development Sites
Class 5 and Above Wind Resource
Acres of Windy Land by Parcel
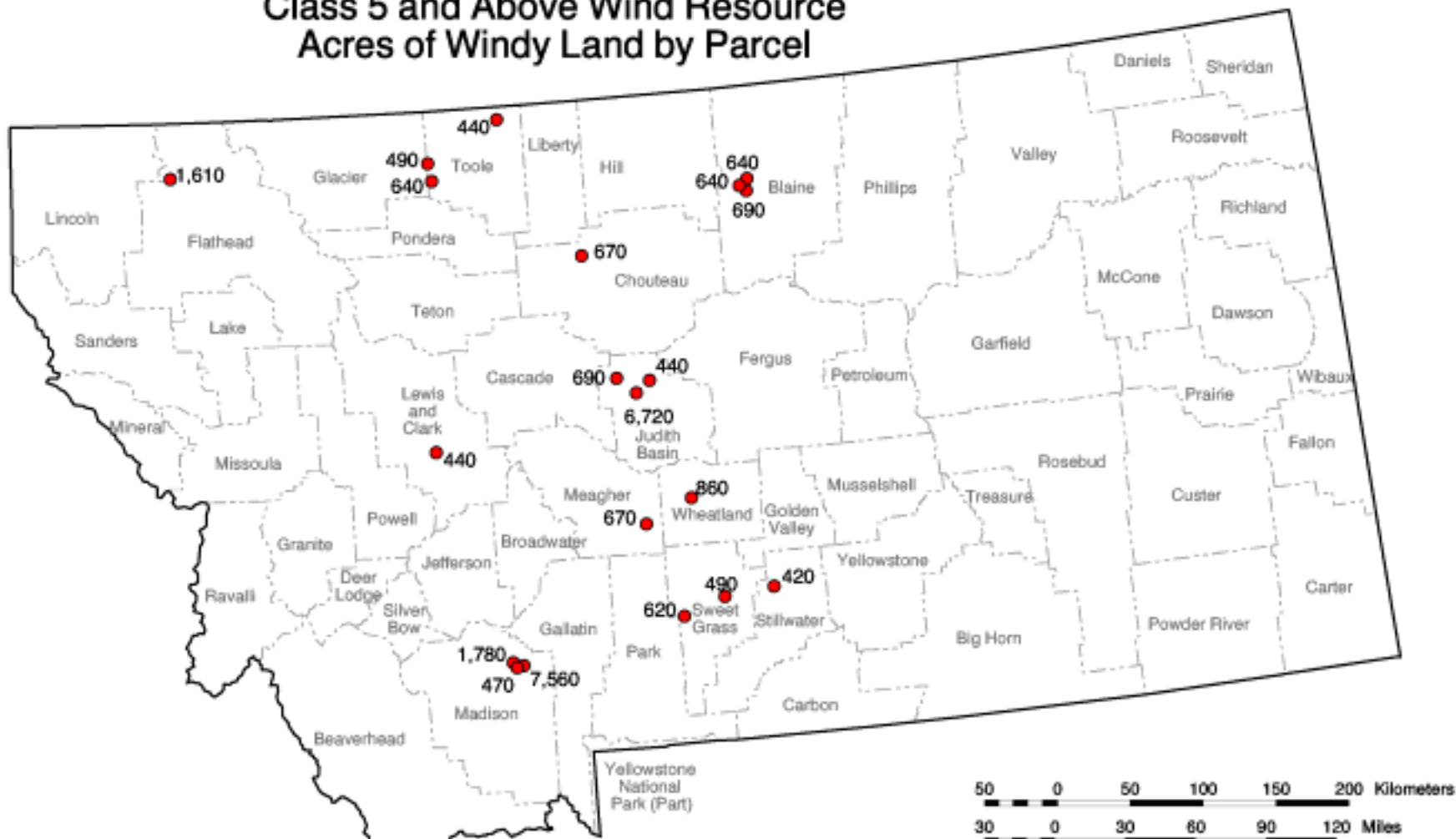
The individual parcels are identified by a
'Stewardship ID' in the Montana Natural
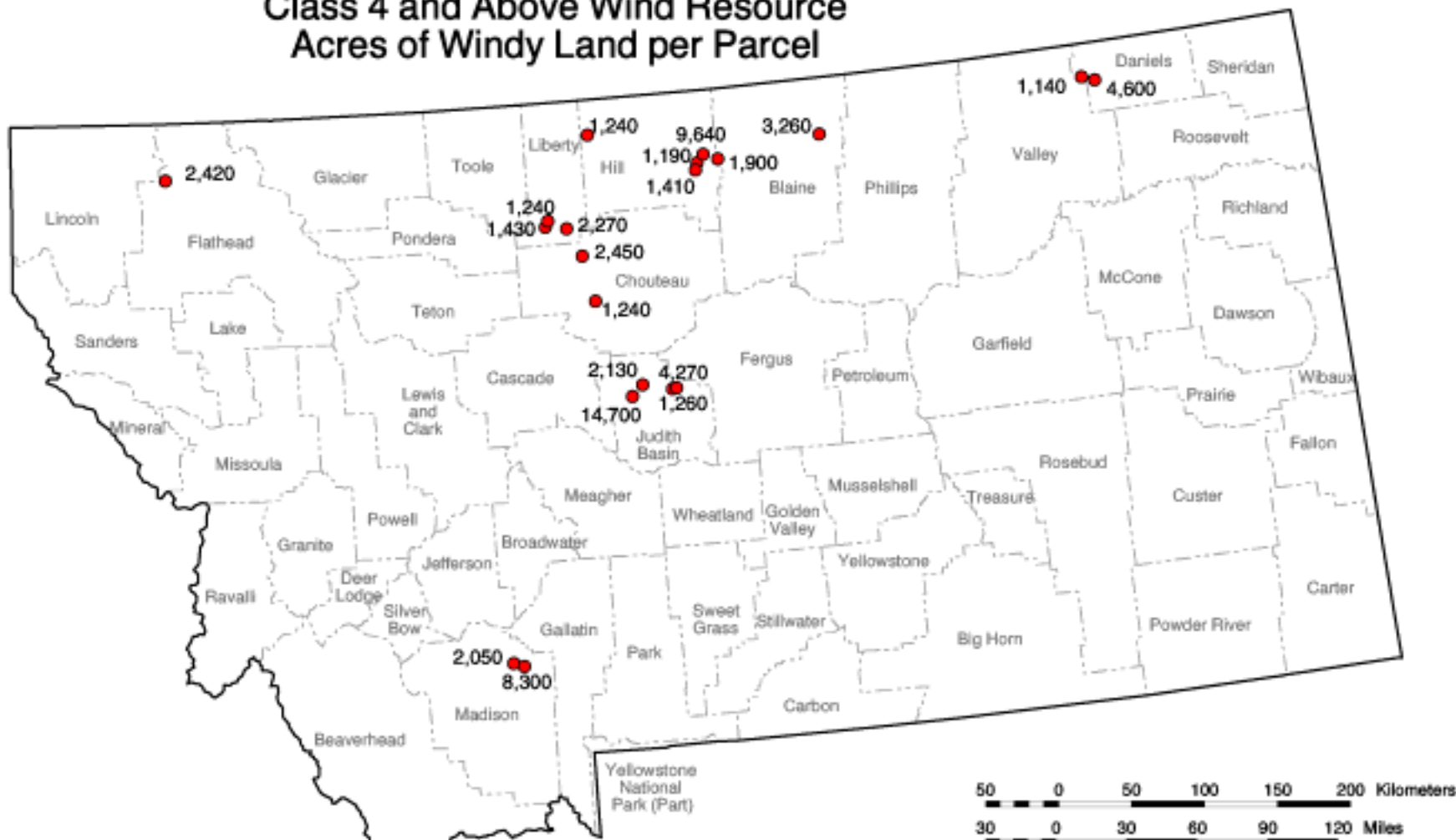Heritage Program's state lands dataset.

Assumptions:
(1) Wind resource class 5 and above.
(2) Within 5 miles of transmission lines 69 kv to 250 kv.
(3) Within 5 miles of paved road.
(4) Not in a wetland area
(5) Montana Fish, Wildlife and Parks land excluded.

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15-MAY-2002 1.1.1

Montana State Lands - Top 20 Potential Wind Development Sites
Class 4 and Above Wind Resource
Acres of Windy Land per Parcel

The individual parcels are identified by a 'Stewardship ID' in the Montana Natural Heritage Program's state lands dataset.

Assumptions:
(1) Wind resource class 4 and above.
(2) Within 5 miles of transmission lines 69 kv to 250 kv.
(3) Within 5 miles of paved road.
(4) Not in a wetland area
(5) Montana Fish, Wildlife and Parks land excluded.

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15-MAY-2002 1.1.2
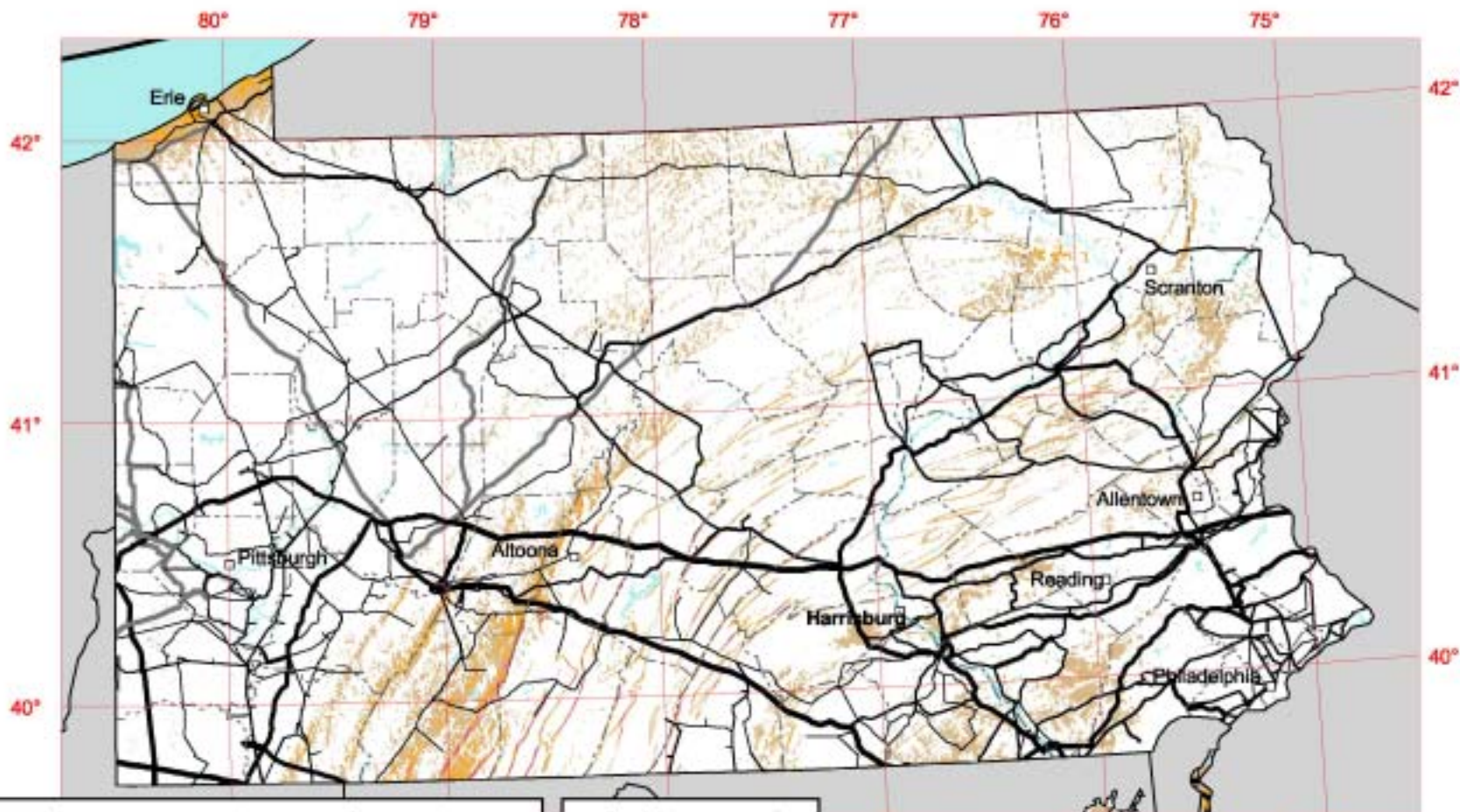
NREL's Updated Wind Resource Assessment Status

Updated Wind
Resource Assessment
Status
Completed
Planned or In Progress

U.S. Department of Energy
National Renewable Energy Laboratory

NREL
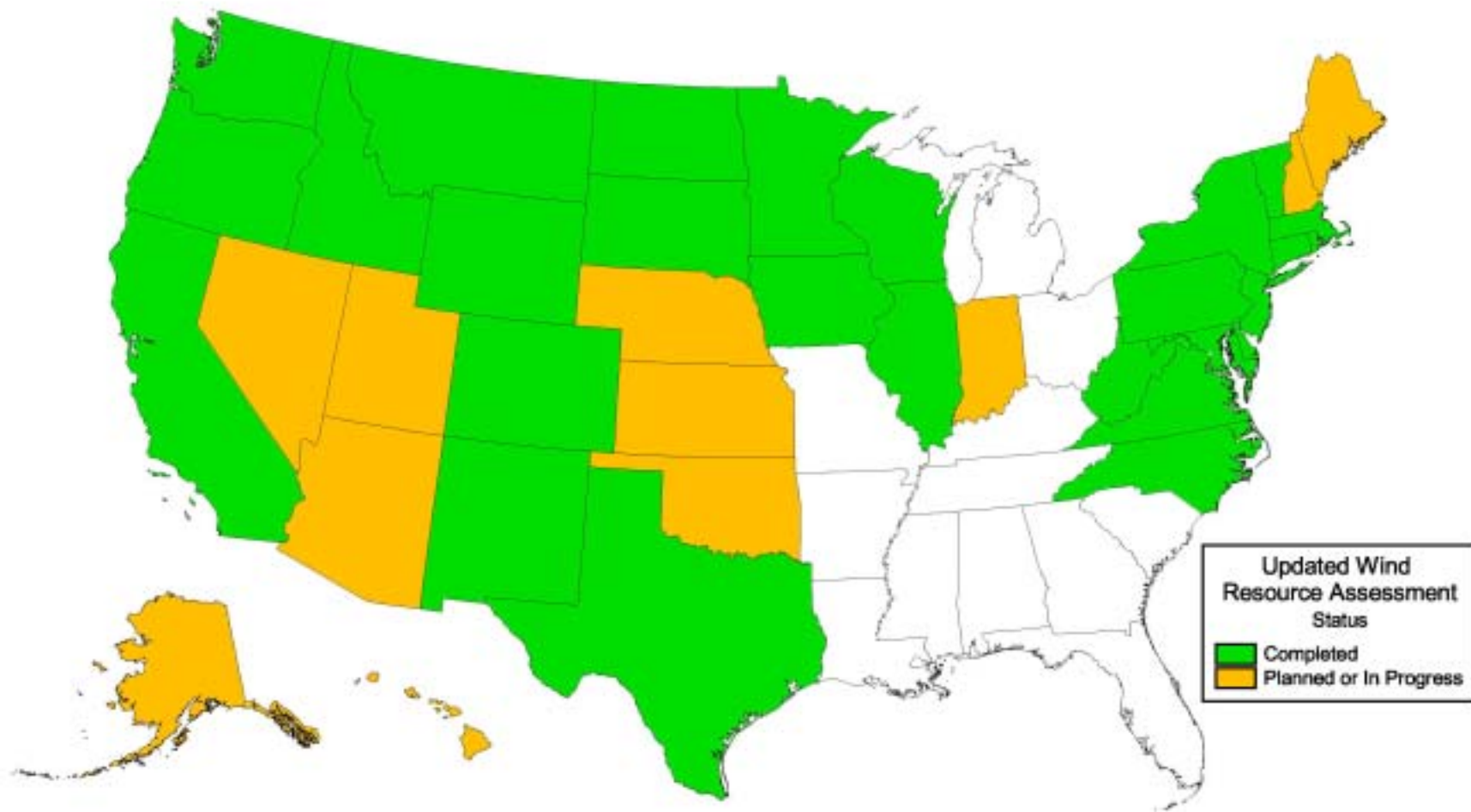
26-DEC-2002 1.1.23
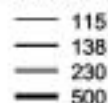
Pennsylvania - 50 m Wind Resource Map

Wind Power Classification

Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m²	Wind Speed [a] at 50 m m/s	Wind Speed [a] at 50 m mph
1	Poor	0 - 200	0.0 - 5.6	0.0 - 12.5
2	Marginal	200 - 300	5.6 - 6.4	12.5 - 14.3
3	Fair	300 - 400	6.4 - 7.0	14.3 - 15.7
4	Good	400 - 500	7.0 - 7.5	15.7 - 16.8
5	Excellent	500 - 600	7.5 - 8.0	16.8 - 17.9
6	Outstanding	600 - 800	8.0 - 8.8	17.9 - 19.7
7	Superb	> 800	> 8.8	> 19.7

[a] Wind speeds are based on a Weibull k value of 2.0

Transmission Line*
Voltage (kV)
- 115
- 138
- 230
- 500

* Source: POWERmap.©2002 Platts, a Division of the McGraw-Hill Companies
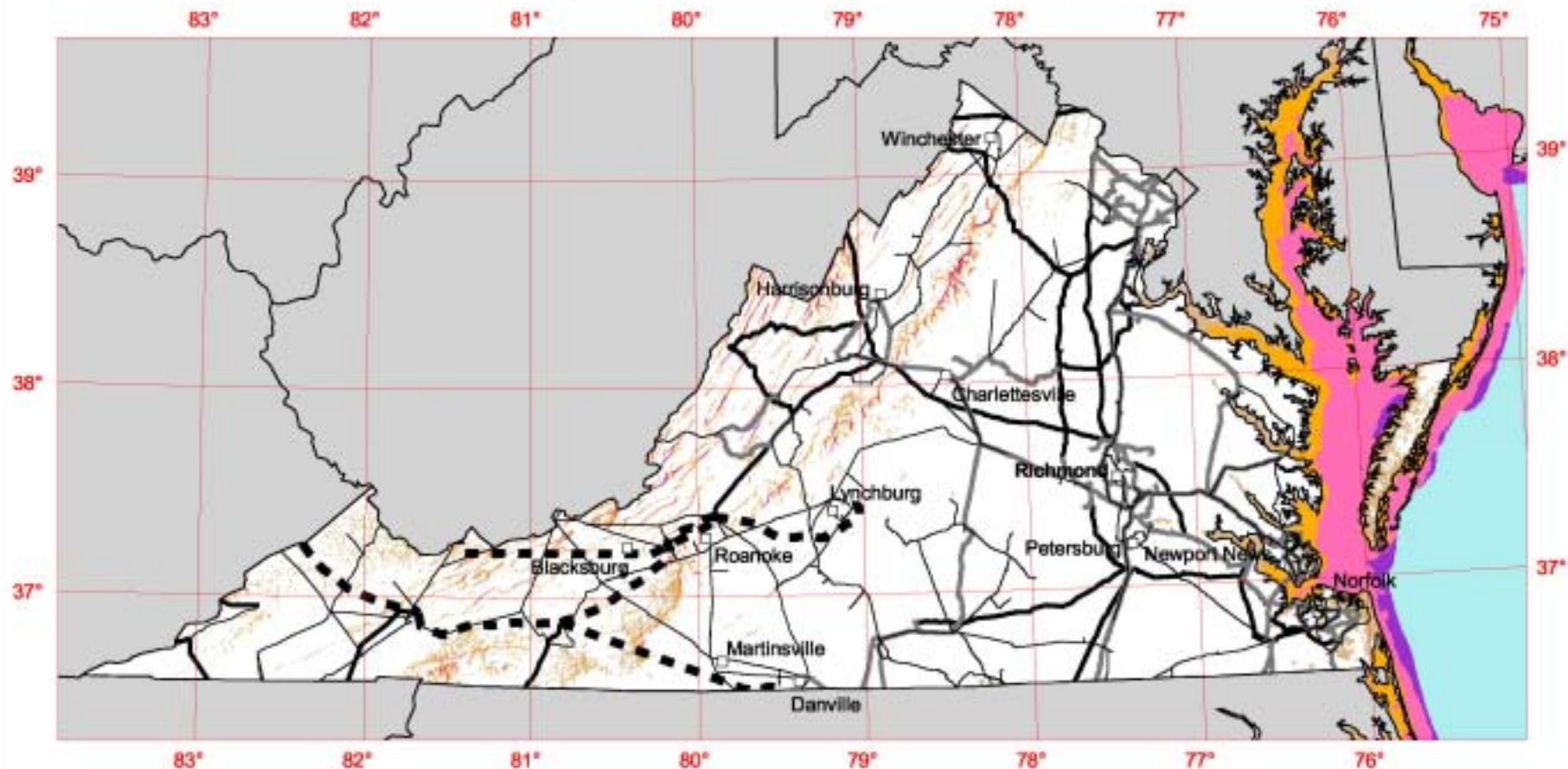
The annual wind power estimates for this map were produced by TrueWind Solutions using their Mesomap system and historical weather data. It has been validated with available surface data by NREL and wind energy meteorological consultants.

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12-JAN-2003 1.14.1

Virginia - 50 m Wind Resource Map

Wind Power Classification

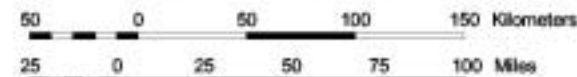| Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m²	Wind Speed [a] at 50 m m/s	Wind Speed [a] at 50 m mph
1	Poor	0 - 200	0.0 - 5.6	0.0 - 12.5
2	Marginal	200 - 300	5.6 - 6.4	12.5 - 14.3
3	Fair	300 - 400	6.4 - 7.0	14.3 - 15.7
4	Good	400 - 500	7.0 - 7.5	15.7 - 16.8
5	Excellent	500 - 600	7.5 - 8.0	16.8 - 17.9
6	Outstanding	600 - 800	8.0 - 8.8	17.9 - 19.7
7	Superb	> 800	> 8.8	> 19.7

[a] Wind speeds are based on a Weibull k value of 2.0

Transmission Line*
Voltage (kV)
- 115 - 138
- 161
- 230
- 500
- 765

* Source: POWERmap,©2002 Platts, a Division of the McGraw-Hill Companies

The annual wind power estimates for this map were produced by TrueWind Solutions using their Mesomap system and historical weather data. It has been validated with available surface data by NREL and wind energy meteorological consultants.

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12-JAN-2003 1.1.1